ANSI/AIAA
S-081-2000

Standard

Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

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American National Standard

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Sponsored by

American Institute of Aeronautics and Astronautics

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Abstract

This standard establishes baseline requirements for the design, fabrication, test, inspection, operation, and maintenance of composite overwrapped pressure vessels (COPVs) used for pressurized, hazardous or non-hazardous, liquid or gas storage in space systems such as spacecraft and launch vehicles. These requirements when implemented on a particular system will assure a high level of confidence in achieving safe and reliable operation.

American National Standard

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Foreword

This document was prepared following a draft military standard, Mil-Std-1522B (USAF), dated 14 July 1995, entitled Requirements for “Design and Operation of Pressurized Missile and Space Systems,” developed by The Aerospace Corporation, El Segundo, California, under USAF contract F04701-88-C-0089. James B. Chang was the principle investigator of this development effort. This contract was administered by the Air Force Space and Missile Systems Center (AF/SMC), Los Angeles, California. Dr. L. C-P Huang was the Air Force Project Manager. That military standard was never released officially. It is not being replaced by a series of American National Standards including this one.

The AIAA Aerospace Pressure Vessel Standard Working Group operates within the AIAA Structures Committee on Standards. It was formed in March 1996 with an emphasis on inclusion of aerospace prime companies, pressure vessel suppliers, and all interested government agencies. Deliberations focused heavily on adapting the standard to address commercial procurement of aerospace pressure vessels. One of the goals of the project was to provide a performance standard, which could be used by commercial launch operators in seeking licenses from the US Department of Transportation. Another goal was to assist the US Department of Defense in its transition to procuring aerospace hardware on a commercial basis to the maximum extent possible.

The AIAA Standards Procedures provide that all approved Standards, Recommended Practices, and Guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement to adhere to any AIAA standards publication and no commitment to conform to or be guided by any standards report. In formulating, revising, and approving standard publications, the Committees on Standards will not consider patents, which may apply to the subject matter. Prospective users of the publications are responsible for protecting themselves against liability for infringement of patents or copyrights, or both.

At the time of approval of this Standard, the AIAA Aerospace Pressure Vessel Standards Working Group included the following members: (* Member of the Editing Committee)

Hank Babel (The Boeing Company) *

Harold Beeson (NASA White Sands Test Facility)

Celia Blum (Lockheed Martin Michoud)

Robert Breaux (Kaiser Compositek)

James Chang (Aerospace Corporation) *

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This document was accepted for publication by the Standards Executive Council on January 11, 2001.

1 Scope

1.1 Purpose

This standard establishes baseline requirements for the design, fabrication, test, inspection, operation, and maintenance of composite overwrapped pressure vessels (COPVs) used for pressurized, hazardous or non-hazardous, liquid or gas storage in space systems such as spacecraft and launch vehicles. These requirements, when implemented on a particular system, will assure a high level of confidence in achieving safe and reliable operation.

1.2 Application

This standard is applicable to metal-lined COPVs used for space flight. A companion standard, ANSI/AIAA S-080-1998, shall be used for the metallic liner**,** as specified in the body of this standard. Throughout this document, the term COPV is used specifically for a metal-lined COPV. Specialized pressurized equipment such as batteries, heat pipes, cryostats, and sealed containers are not included.

It is not the intent of this document to infer that COPVs with non-metal liners are not acceptable for aerospace applications. It is expected that COPVs with non-metal liners will reflect equivalent design, manufacture, test, safety, and use requirements as those for metal-lined COPVs, as applicable.

The requirements specified in this standard may be tailored to specific programs with agreement of the appropriate approval authority.

2 Reference Documents

The latest issues of the following documents are referenced for establishing pressure vessel designs, analyses, demonstrations, and tests.

2.1 Government Documents

Mil-Hdbk-17, Polymer Matrix Composites, Three Volumes

2.2 Non Government Documents

ANSI/AIAA S-080-1998, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

3 Vocabulary

The following definitions of significant terms are provided to ensure precision of meaning and consistency of usage. In the event of a conflict, the definitions listed below take precedence:

A Basis Allowable: The mechanical strength values such that 99% of the population will meet or exceed the specified values with a confidence level of 95%.

Acceptance Tests: The required formal tests conducted on flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for intended usage.

Allowable Load (Stress): The maximum load (stress) that can be accommodated by a structure (material) without rupture, collapse, or detrimental deformation in a given environment. Allowable loads (stresses) commonly correspond to the statistically based minimum ultimate strength, buckling strength, and yield strength, as applicable.

Autofrettage: A sizing pressure operation where pressure driven deflection is used to plastically yield the metal liner into the overlying composite in order to induce initial stress states in the metal liner and composite.

Burst Factor (BF): A multiplying factor applied to the Maximum Expected Operating Pressure (MEOP) to obtain the design burst pressure.

Composite-Overwrapped Pressure Vessel (COPV): A pressure vessel with a composite structure fully or partially encapsulating a metallic liner. The liner serves as a fluid (gas or liquid) permeation barrier and may or may not carry substantive pressure loads. The composite generally carries pressure and environmental loads.

Damage Control Plan: A plan that defines the damage threats to a COPV during manufacturing, integration, transportation up to the time of launch and the steps taken to minimize the possibility of damage due to these threats.

Damage Tolerance: The ability of a COPV to sustain a level of damage or presence of a defect and yet be able to perform.

Design Burst Pressure: The differential pressure that a COPV must withstand without rupture in the applicable operating environment. It is equal to the product of the MEOP and a burst factor.

Design Safety Factor: A multiplying factor applied to the limit load and/or MEOP for the purpose of analytical assessment and/or test verification of structural adequacy.

Destabilizing Pressure: A differential pressure that produces compressive stresses in a pressurized structure.

Detrimental Deformation: The detrimental deformation, deflection, or displacement that prevents any portion of the COPV from performing its intended function or that reduces the probability of successful completion of the mission.

Development Test: A test that is conducted by the manufacturer in order to provide design information that may be used to check the validity of analytic techniques and assumed design parameters; to uncover unexpected system response characteristics; to evaluate design changes; to determine interface compatibility; to prove qualification and acceptance procedures and techniques; or to establish accept/reject criteria for non-destructive inspection (NDI); or any other purpose necessary to establish the validity of the design and manufacturing processes.

Dynamic Envelope: The space or volume allocated to a component, which includes allowance for all displacements and deflections associated with the worst case combination of loading.

Environments: The environmental exposures (such as humidity, temperature, and radiation levels) which the COPV is subjected to after completion of manufacture and final inspection.

Elastically Responding Metallic Liner: A metallic liner of a COPV that responds elastically (i.e., experiences no plastic response) after the autofrettage operation at all pressure up to and including vessel proof pressure.

Flaw: A local discontinuity in a structural material such as a scratch, notch, or crack.

Hazard: An existing or potential condition that may result in a mishap.

Hazardous Fluid/Material: A liquid or gas that may be toxic, reactive, or flammable either by itself or in combination with other materials.

Impact Damage (ID): An induced fault in the composite overwrap or metallic liner, which is caused by an object strike on the vessel or vessel strike on an object and is a subset of mechanical damage.

Leak-Before-Burst (LBB): A design concept in which any initial flaw will grow through the wall of a metallic liner of a COPV at or below MEOP and cause pressure relieving leakage rather than burst or rupture.

Limit Load: The maximum expected external load or combination of loads, which a structure may experience during the performance of specified missions in specified environments. When a statistical estimate is applicable, the limit load is that load not expected to be exceeded at 99% probability with 90% confidence.

Loading Spectrum: A representation of the cumulative loading anticipated for the COPV under all expected operating environments. Significant transportation and handling loads are included.

Margin of Safety (MS):

$$MS = \frac{AllowableLoad}{LimitLoad \times DesignSafetyFactor} - 1$$

Note: load may mean stress or strain.

Maximum Expected Operating Pressure (MEOP): The maximum pressure that a pressure vessel is expected to experience during its service life in association with its applicable operating environments.

Maximum Design Pressure (MDP): The highest possible operating pressure considering maximum temperature, maximum relief pressures, maximum regulator pressure, and, where applicable, transient pressures excursions. (MDP for Space Shuttle is a two failure tolerant pressure, i.e., will accommodate any combination of two credible failures that will affect pressure during association with the Space Shuttle.) MDP also accommodates the maximum temperature to be experienced in the event of an abort to a site without cooling facilities.

Mechanical Damage: An induced fault in the composite overwraps or metallic liner, which is caused by surface abrasions, cuts or impacts.

Plastically Responding Metallic Liner: A metallic liner of a COPV that experiences plastic response after the autofrettage operation at any pressure up to and including the vessel's acceptance proof pressure.

Pressure Vessel: A container designed primarily for the storage of pressurized fluids which (1) contains stored energy of 14,240 foot pounds (19,310 joules) or greater, based on adiabatic expansion of a perfect gas, or (2) contains gas or liquid which will create a mishap (accident) if released, or (3) will experience a MEOP greater than 100 psi (700 kPa).

Procurement Agency: The organization that places a manufacturer on contract to design, qualify, test, and fabricate the COPV.

Qualification Tests: The required formal contractual tests used to demonstrate that the design, manufacturing, and assembly have resulted in a design that conforms to specification requirements.

Residual Strength: The maximum value of nominal load (stress) that a cracked or damaged body is capable of sustaining without failure.

Residual Stress: The stress that remains in a structure after processing, fabrication, assembly, testing, or operation; for example welding induced residual stress.

Safe-Life: The required period of time or number of cycles that the metallic liner of a COPV containing the largest undetected crack shown by analysis or testing will not leak or fail catastrophically in the expected service load and environment.

Service Life: The period of time or number of cycles which starts with the completion of physical assembly or acceptance testing with the associate determination of the state or nature of pre-existing flaws based on NDI or flaw-screening proof test and continues through all subsequent exposure environments, including as applicable, handling, storage, transportation, service environments, refurbishment, re-testing, reentry or recovery from orbit, and reuse.

Sizing Pressure: The pressure to which a COPV is subjected with the intent of yielding the metal liner or a portion of the liner of the COPV. The sizing operation, also referred to as autofrettage, is considered to be part of the manufacturing process and is conducted prior to acceptance proof testing.

Stress-Corrosion Cracking: A mechanical-environmental induced failure process in that sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw in a metal part.

Stress Intensity Factor (K): A parameter that characterizes the stress-strain behavior at the tip of a crack contained in a linear elastic, homogeneous, and isotropic body.

Stress Ratio: The ultimate strength of the fiber, as determined in pressure vessel burst tests, divided by the stress in the fiber at MEOP.

Stress Rupture Life: The minimum time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environments.

Trained Inspector: An inspector who has had training to detect visible damage on COPVs. The training shall involve the use of actual damaged vessels.

Ultimate Load: The product of the limit load and the design safety factor for ultimate. It is the load, which the structure must withstand without rupture or collapse in the expected operating environments.

Visual Damage Threshold (VDT): An impact energy level shown by test(s) that creates an indication that is (barely) detectable by a trained inspector using an unaided visual technique. (It is noted that no quantitative reliability or confidence level is associated with this technique.)

4 General Requirements

This standard presents the general requirements for the design, analysis, and verification of COPVs. The results of all analyses and tests shall be documented in reports containing all significant and relevant data, methods, models, assumptions, and results.

4.1 System Analysis Requirements

A system analysis shall be performed per the applicable requirements of Section 4.1 of ANSI/AIAA S-080 to establish design and performance requirements for the COPV.

4.2 General Design and Analysis Requirements

One of the two following alternative approaches for the design, analysis and verification of COPVs shall be selected:

(a) LBB or safe-life for non-hazardous fluid applications,

(b) Safe-life for hazardous fluid applications.

4.2.1 Loads, Pressures, and Design Environments

The anticipated load-pressure-temperature history and associated environments throughout the service life shall be used to define the design load/environment spectra that shall be used for both design analysis and testing. Updates to the design spectra shall be evaluated to ensure positive margins prior to flight. Environmental testing (i.e. vibration, acoustic, shock, equivalent static load, etc.) shall be conducted per the direction of the procurement agency. The procurement agency shall select the tests and provide the environmental loads and levels. The procurement agency is also responsible for the definition of performance requirements and applicable operational and non-operational environments.

4.2.2 Strength Requirements

All COPVs shall possess sufficient strength to withstand limit loads and simultaneously occurring internal pressures in the expected operating environments throughout their respective service lives without experiencing detrimental deformation. They shall also withstand ultimate loads and simultaneously occurring internal pressures in the expected operating environments without experiencing rupture or collapse.

They shall be capable of withstanding ultimate external loads and ultimate external pressure (destabilizing) without collapse or rupture when internally pressurized to the minimum launch pressure.

They shall sustain proof pressure without detrimental deformation and shall sustain design burst pressure without burst. When proof tests are conducted at temperatures other than the design temperatures, the change in material properties at the proof test temperature shall be accounted for in determining proof pressure. The margin of safety shall be positive and shall be determined by analysis or test at ultimate and limit load levels at the temperature expected for all critical conditions, when appropriate.

The margins of safety shall be based on A-basis allowables.

The minimum burst factor shall be 1.5. The stress rupture requirements of Section 4.2.8 shall also apply.

4.2.3 Stiffness Requirements

COPVs shall possess adequate stiffness to preclude detrimental deformation at limit loads and at pressures in the expected operating environments throughout their respective service lives. The stiffness properties of the mounted COPV shall be such as to prevent all detrimental instabilities of coupled vibration modes. This is to minimize detrimental effects of the loads and dynamics response, which are associated with structural flexibility of the vessel and its interface mounting, and to allow the vessel to remain within the specified static and dynamic envelope.

4.2.4 Thermal Requirements

Thermal effects, including heating and cooling rates, temperatures, thermal gradients, thermal stresses and deformations, and changes in the physical and mechanical properties of the materials of construction, shall be considered in the design of all COPVs. These effects shall be based on temperature extremes predicted for the operating environment plus a design margin as appropriate.

4.2.5 Stress Analysis Requirements

A detailed and comprehensive stress analysis of each COPV design shall be conducted with the assumptions that no crack-like flaws exist in the metallic liner, and there are no defects in the overwrap. The analysis shall determine stresses resulting from the combined effects of internal pressure, ground or flight loads, temperatures, and thermal gradients. Both membrane stresses and bending stresses resulting from internal pressure and external loads shall be calculated to account for the effects of geometrical discontinuities, design configuration, and structural support attachments. The analysis shall include the effects of adding stresses from restraints, manufacturing tolerances, test conditions, residual stresses, and assembly stresses. Thermal effects, including heating rates, temperatures, thermal gradient, thermal stresses and deformations, and changes in the physical and mechanical properties of the material of construction shall be considered in the stress analysis.

Loads shall be combined by using the appropriate design safety factors on the individual loads and comparing the results to A basis allowables. Design safety factors on external (support) loads shall be as assigned to primary structure supporting the pressurized system.

Finite element or other proven equivalent structural analysis techniques shall be used to calculate the stresses, strains, and displacements for complex geometries and loading conditions. Local structural models shall be constructed, as necessary, to augment the overall structural model in areas of rapidly varying stresses. The analysis tools used for the structural assessment shall be correlated against past test results for the class of vessel shape and lamination analyzed to demonstrate the accuracy of the methodology. The analytical tool verification shall be submitted as part of the analysis report.

Elastically responding regions of the metallic liner shall be analyzed according to the requirements of ANSI/AIAA S-080, Section 4.2.5. Residual stresses shall be considered in the stress analysis.

Plastically responding regions of the metallic liner shall meet all requirements defined in this document. Residual stresses shall be considered in the stress analysis.

A methodology using composite laminate theory shall be employed to analyze the composite. Effects of ply orientation, stacking sequence, and geometrical discontinuities shall be assessed.

The effect of variation in thickness gradients and in material thickness, as specified in the design documentation, shall be used in calculating the stresses and strains in the liner and composite.

The margins of safety shall be positive for all load conditions on the COPV

4.2.6 Fatigue-Life Requirements

A fatigue analysis is required to demonstrate the fatigue life of an unflawed COPV. Nominal values of fatigue-life characteristics for metal liners and composite overwraps including stress-life (S-N) data and/or strain-life (ε - N) data of the structural materials shall be used. These data shall be taken from reliable sources such as Mil-Hdbk-5, the Aerospace Structural Metals Handbook, and Mil-Hdbk-17. The analysis shall account for the spectra of expected operating loads, pressures, and environments. The conventional fatigue damage accumulation technique, Miner's rule ($\Sigma n/N$), is an acceptable method for handling variable amplitude fatigue cyclic loading. Unless otherwise specified, a life factor of four (4) shall be used in the fatigue analysis. The limit for accumulated fatigue damage shall be 80% of the normal limit.

For elastically responding metal liners, the requirements of ANSI/AIAA S-080, Section 4.2.6 shall be used for the analysis. For plastically responding metallic liners, the analysis shall address all strain excursions for all spectra of expected operating loads, pressures, and environments. For the composite elements of the COPV, the analysis shall address the alternating stress response for all spectra of expected operating loads, pressures, and environments.

Testing of unflawed specimens to demonstrate fatigue-life of specific hardware together with stress analysis is an acceptable alternative to analytical prediction. Fatigue-life requirements are considered demonstrated when the unflawed specimens successfully sustain the limit loads and MEOP in the expected operating environments for the specified test cycles and duration without rupture. Unflawed specimens shall represent critical areas such as membrane section, weld joints, heat-affected zone, and boss transition section, including representative overwrap layers as appropriate. The required test duration is four (4) times the specified service life or number of cycles.

4.2.7 Safe-Life Requirements

Safe-life requirements shall apply only to the metallic liner and to integral bosses. The overwrap shall be assumed to be unflawed. For elastically responding metallic liners and integral bosses, and for elastically responding regions of a generally plastic responding liner, the safe life requirements of ANSI/AIAA S-080, Section 4.2.7 shall apply.

For plastically responding regions of metallic liners, testing is the only acceptable method to demonstrate safe-life since no generally accepted elastic/plastic analytical method is available. The test requirements of Section 5.1 shall apply.

A life factor of four (4) shall be used in the safe-life testing. For those COPVs, which are readily accessible for periodic inspection and repair, the safe-life shall be at least four (4) times the interval between scheduled inspection and/or refurbishment.

A safe-life report shall be prepared to delineate the following:

(a) Loading spectrum and environments;

(b) Non-destructive evaluation (NDE) method(s) and corresponding initial flaw sizes;

(c) Strain analysis assumptions and rationale;

(d) Summary of significant results;

References;

Material property reference list; and

Summary of test data generated in support of safe life assessment.

This report shall be closely coordinated with the stress analysis report.

4.2.8 Stress-Rupture Requirements

The COPV shall be designed to meet the design life considering the time it is under sustained load. There shall be no credible stress rupture failure modes based on stress rupture data for a probability of survival of 0.999.

To meet the stress rupture requirements, the lowest fiber reinforcement stress ratio at MEOP shall be:

Carbon = 1.5

Aramid = 1.65

Glass = 2.25

Other materials shall have stress rupture data and reliability analysis comparable to the materials listed above to support a given stress ratio at MEOP.

4.2.9 Leak-Before-Burst Requirements

When Leak-Before-Burst (LBB) is chosen as the COPV design approach, only the regions of the COPV liner that are covered by the composite are required to exhibit a LBB failure mode at MEOP. Specifically, the areas of a boss which are not covered by the composite and remain elastic at all pressures in the service life shall be designed per Section 4.2.7 for safe-life or this section for LBB. The shear region of the boss that is under the composite where the internal pressure is trying to shear the boss through the opening of the composite shall be excluded from both safe-life and LBB design requirements.

When the liner remains elastic at all pressures and/or loads in the service life, linear elastic fracture mechanics shall be used to show that both of the following conditions are satisfied:

(a) An initial part through crack (surface flaw) with a shape (a/2c) ranging from 0.1 to 0.5 shall not fail (cause catastrophic burst) at any stress intensity factor applied during the service life ($K<K_{Ic}$ at all times), and

(b) This part-through crack shall grow through the wall of the pressure vessel liner to become a through crack with a length equal to ten times the wall thickness thereby leaking out the contents before catastrophic failure (burst) can occur.

4.2.10 Damage Control Requirements

COPVs with a burst factor of 4.0 or greater and a total wall thickness of 0.25 inch (6 mm) or greater are exempted from the requirements of Section 4.2.10.

Mechanical damage that may degrade the performance of the COPV below the minimum strength requirements of Section 4.2.2 shall be prevented. A damage control plan in accordance with Section 4.2.10.1 is mandatory.

For mechanical damage mitigation, a minimum of one of the following approaches shall be adapted**:**

(a) Mechanical Damage Protection/Indication

(b) Damage Tolerance Demonstration

These two approaches are described below.

A mechanically damaged COPV requires procurement agency Material Review Board (MRB) approval prior to use.

4.2.10.1 Damage Control Plan

The damage control plan shall document the threat analysis and procedures that mitigate these threats. The threat analysis shall document the conditions (source and magnitude of threat and state of pressurization of the COPV) under which mechanical damage can occur. The Damage Control Plan shall delineate all potentially damaging events and investigate mitigating procedures.

4.2.10.2 Approach A - Mechanical Damage Protection/Indication

Protective covers shall provide isolation from a mechanical damage event. Protective covers shall be used when the COPV has not demonstrated sufficient strength per Section 4.2.2 after a mechanical damage incident that is consistent with the worst case credible threat identified in Section 4.2.10.1. The following requirements shall apply for protective covers and /or indicators:

4.2.10.2.1 Protective Covers

The effectiveness of protector covers shall be demonstrated by test.

Protective covers or standoffs which isolate the vessel are required when personnel will be exposed to pressurized COPVs having stored energy levels in excess of 14,240 ft-lbf (19, 310 joules) or containing hazardous fluids. They shall be designed to completely protect the COPV under the worst credible threat defined in Section 4.2.10.1. They shall allow transmission of less than 5 ft-lbf (6.8 joules) of energy or reduce the transmitted energy to a level not to exceed one half that demonstrated as acceptable by pressurized damage tolerance or residual strength testing.

Protective covers shall not be removed until the latest practical time prior to launch or during other critical operations requiring cover removal.

4.2.10.2.2 Indicators

When protective covers are not used, or the indicators are placed between the protective cover and the COPV, the effectiveness of the indicators to provide positive evidence of a mechanical damage event less than or equal to the demonstrated residual strength capability of the unprotected COPV shall be demonstrated by test. If residual strength testing of the COPV is not performed, the indicators shall be capable of detecting a 5 ft-lbf (6.8 joule) impact with a 0.5 in. (13-mm) diameter steel hemispherical tup impactor.

When indicators are placed outside of the protective cover, the effectiveness of the indicator to provide a positive evidence of impact in excess of the cover isolation capability shall be demonstrated by test.

The use of indicators as the sole means of mitigating threats for pressurized COPVs, as defined in Section 4.2.10.1, during personnel workaround is prohibited.

4.2.10.3 Approach B Damage Tolerance Demonstration

Mechanical damage tolerance demonstration is an alternative to, or complementary with, mechanical damage covers to satisfy the requirements for damage control.

4.2.10.3.1 Impact Damage Tolerance Demonstration

Impact damage shall be induced using a drop type impactor and a 0.5-in. (13-mm) diameter, steel hemispherical tup. A pendulum-type arrangement may be used if an analysis substantiates energy and momentum levels equivalent to a drop test. The minimum energy level shall be the greater of the worst case threat, or visual damage threshold (VDT). After inducing damage to the COPV, verification of the capability to satisfy the strength requirements of Section 4.2.2 shall be demonstrated by test. The damage shall be induced in the most damage critical condition (e.g. pressurized vs. unpressurized) and location.

4.2.10.3.2 Other Mechanical Damage Tolerance Demonstration

Damage tolerance of other mechanical damage such as abrasions and surface cuts shall be demonstrated by analysis or test to verify the strength requirements of Section 4.2.2. The abrasion or cut shall be based on the threat analysis of Section 4.2.10.1.

4.2.11 Corrosion and Stress Corrosion Control and Prevention

Operational, test, and manufacturing support fluids that come in contact with the COPV shall be identified, along with the frequency of contact, duration of contact, and fluid temperatures. These fluids shall be compatible with the liner and composite material and not result in stress corrosion cracking or sustained-load failure. Compatibility of the metal liner shall be evaluated as specified in Section 5.2.1.3

Degradation of the COPV from corrosive or incompatible environments shall be prevented and shall meet the requirements specified in Section 5.2.1.3. The design of the COPV shall provide for isolation of the liner from electrically conductive elements in the reinforcing composite matrix.

4.2.12 Embrittlement Control

All known embrittlement mechanisms, such as hydrogen embrittlement, liquid-metal embrittlement, etc. applicable to the liner, fiber, and resin shall be identified and controlled in the design, fabrication, and operation of the COPV.

4.3 Materials Requirements

4.3.1 Metallic Materials

The metallic liner material shall be selected, evaluated, characterized, and controlled per the criteria of Section 4.3.1 of ANSI/AIAA S-080.

4.3.2 Composite Materials

4.3.2.1 Composite Materials Selection

Composite material systems used for COPVs, consisting of a reinforcing filament material impregnated by a resin matrix, shall be selected on the basis of proven environmental compatibility, material strength/modulus, stress rupture properties, and compatibility with metal liner materials. If electrically conductive fiber reinforcement is used, the design shall incorporate a means to prevent galvanic corrosion with metallic components.

The effects of fabrication processes, coatings, fluids and the effects of temperature, load spectra, impact spectra, and other environmental conditions which affect the strength and stiffness of the material in the fabricated configuration shall also be included in the rationale for selecting the composite material system.

4.3.2.2 Composite Material System Characterization

The composite materials selected for the design shall be evaluated with respect to the material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, operating environments and other pertinent factors which affect the resulting strength and stiffness properties of the material in the fabricated as well as refurbished configurations. The properties of the composite materials selected shall be characterized in sufficient detail to permit reliable and high confidence predictions of the structural performance in their expected operating environments. The supporting data shall provide justification for the declared properties consistent with the operating and non-operating environments.

4.3.2.2.1 Characterization Tests

Uniform test procedures shall be employed for determining material properties as required. These procedures shall conform to a recognized standard. Deviations from standard procedures shall be documented. The test specimens and procedures utilized shall provide valid test data for the intended application.

4.3.2.2.2 Strength Design Allowables

A-basis strength allowables shall be determined from burst testing of sub-scale and/or full-scale composite vessels. If the A-basis fiber strength was developed from sub-scale vessels, or if the full-scale COPV differs in configuration from the A-basis fiber vessels (e.g. cylinder vs. sphere) then it must be shown analytically that the A-basis fiber strength is valid for the full scale COPV or the A-basis allowable must be adjusted to account for differences between the full scale COPV and the A-basis vessels. This data shall be used to establish ultimate strength for the fiber/resin system.

The A-basis allowables shall be calculated per the procedures in Mil-Hdbk-17 and shall include the test results from at least two lots of materials unless all of the vessels are produced from the same lot of material. The results from production vessels of different configurations and sub-scale pressure vessels may be pooled together.

A change in the resin system shall require testing of a minimum of three sub-scale and/or full scale vessels. The population of the mean delivered strength using the new resin system shall be compared to the original delivered strength. The populations are considered equivalent if the variances and means pass the tests of equality (i.e., Levene's test and the F-test) as described in Mil-Hdbk-17.

4.4 Fabrication and Process Control

The design of all COPVs shall employ proven processes and procedures for manufacture. Mil-Hdbk-17 shall be used as appropriate to address fabrication and process control measures. It is the responsibility of the COPV manufacturer to demonstrate that the processes are qualified for the fabrication of the COPV.

The fabrication process shall provide for initial and in-process inspections, and periodic in-service inspection to support safe operation and high probability for mission success.

4.4.1 Liner Fabrication and Process Control

The requirements, as levied by ANSI/AIAA S-080, Section 4.5, shall apply to metallic liner fabrication and process control.

4.4.2 Overwrap Fabrication and Process Control

The composite overwrap fabrication process shall be a controlled documented process. Incorporated materials shall have certifications that demonstrate acceptable variable ranges to ensure repeatable and reliable performance. An inspection plan shall be developed per Section 4.5.1 to identify all critical parameters essential for verification.

In-process inspection or process monitoring shall be used to verify the setup, and the acceptability of critical parameters during the filament winding process.

The amount of each composite material used on the article from the composite fabrication shall be verified. The fabrication process shall control or eliminate detrimental conditions in the fabricated article.

4.5 Quality Assurance

A quality assurance or inspection program as defined by ANSI/AIAA S-080; Section 4.6 shall be implemented. The following shall be included in the quality assurance program.

4.5.1 Inspection Plan

An inspection master plan shall be established prior to start of fabrication. The plan shall specify appropriate inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance-proof test, and operation, as appropriate. In establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, structural configuration, corrosion control, and accessibility for inspection of flaws. Acceptance and rejection standards shall be established for each phase of inspection, and for each type of inspection technique.

4.5.2 Inspection Techniques

The selected NDI techniques for the metal liner shall be according to Section 4.6.2 of ANSI/AIAA S-080. Inspection shall be performed before overwrapping with composite materials. As a minimum after overwrapping, the NDI technique shall consist of a detailed visual inspection by a trained inspector at the points defined by the damage control plan. Other inspection techniques shall be used when warranted.

The NDI procedures shall be documented and based on using multiple NDI methods when appropriate to perform survey inspections or diagnostic inspections.

The flaw detection capability of each selected NDI technique or combination of NDI techniques as applied to the composite overwrap shall be based on similarity data from prior test programs. Where this data is not available or is not sufficiently extensive to provide reliable results, the capability, under production of operational inspection conditions shall be determined experimentally and demonstrated by tests approved by the procuring agency on representative material product form, thickness, design configuration, and damage source articles. Assessment of composite overwrap damage tolerance that uses quantitative NDI data shall follow the procedure outlined in Section 4.2.10 to determine the accept/reject condition for each type of damage source

4.5.3 Inspection Data

Inspection data shall be maintained throughout the life of the pressure vessel. These data shall be reviewed periodically and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept and structural configuration. The result of this assessment should form the basis of any required corrective action.

4.6 Operations and Maintenance

4.6.1 Operating Procedures

The requirements of ANSI/AIAA S-080, Section 4.7.1 shall be met.

4.6.2 Safe Operating Limits

The requirements of ANSI/AIAA S-080, Section 4.7.2 shall be met.

4.6.3 Inspection and Maintenance During Operation

The results of the appropriate stress, and safe-life analyses shall be used in conjunction with the appropriate results from the structural development and qualification tests to develop a quantitative approach to inspection.

Allowable damage limits shall be established for each COPV so that the required inspection interval and repair schedule can be established to maintain hardware to the requirements of this document. NDI technique(s) and inspection procedures to reliably detect defects and determine flaw size under the condition of use shall be developed for use in the field and depot levels. Procedures shall be established for recording, tracking, and analyzing operational data as it is accumulated to identify critical areas requiring corrective actions. Analyses shall include prediction of remaining life and reassessment of required inspection intervals.

4.6.4 Repair and Refurbishment

When inspections reveal structural damage or defects exceeding the permissible levels, the damaged hardware shall be repaired, refurbished, or replaced, as appropriate. All repaired or refurbished hardware shall be re-certified after each repair and refurbishment by the applicable acceptance test procedure for new hardware to verify their structural integrity and to establish their suitability for continued service. All repair activity shall be a Material Review Board (MRB) activity, which requires approval of the procurement agency.

4.6.5 Storage Requirements

When COPVs are put into storage, shelf life shall be established and based on empirical data. The exposure of COPVs shall be controlled against adverse environments (e.g., temperature, humidity, etc.) which could cause corrosion or other forms of material degradation. In addition, they shall be protected against damage resulting from impacts, scratches, dents, or accidental dropping of the hardware. Induced stresses due to storage fixture constraints shall be minimized by suitable storage fixture design. Significant stresses, defined as those which result in life utilization greater than 0.01% shall be included in the stress report. In the event storage requirements are violated, re-certification shall be required prior to acceptance for use.

Storage requirement violations shall be treated as an MRB activity.

4.6.6 Documentation

The requirements of ANSI/AIAA S-080, Section 4.7.6 shall apply.

5 Verification Requirements

This Section presents the verification analysis and test requirements for COPVs. Quality conformance (inspection and acceptance testing) and qualification requirements, which include design safety factor requirements, failure mode demonstration requirements, pressure cycling, vibration, burst test requirements, and safe-life demonstration requirements are covered.

5.1 Acceptance Test Requirements

Acceptance tests shall be conducted on every COPV to verify workmanship and identify manufacturing defects. Accept/reject criteria shall be formulated prior to tests. The test fixtures and support structures shall be designed to permit application of all test loads without jeopardizing the flightworthiness of the test article. As a minimum, the following tests are required:

(a) General inspection per Section 4.5.1,

(b) Proof pressure testing,

(c) Leak testing.

5.1.1 Non-Destructive Inspection

Every COPV shall be subjected to visual and other non-destructive inspection (NDI), per the inspection plan of Section 4.5.1, to establish the initial and post-proof condition of the fabricated vessel. The inspection shall include a volumetric and surface inspection by the selected NDI techniques.

The selected NDI techniques and inspection sensitivity for the metallic liner shall be according to Section 4.5.2 when safe-life demonstration is required.

The NDI techniques selected for inspecting the composite overwrap of pressure vessels shall be according to Section 4.5.2.

5.1.2 Proof Testing

The COPV shall be proof tested to a minimum pressure of:

P = (1 + Burst Factor)/2 X MEOP (for a burst factor less than 2.0) or

=1.5 X MEOP for a burst factor equal to or greater than 2.0

Unless otherwise stated, the duration of the proof test shall be sufficient to verify pressure stability. The COPV shall not leak, rupture, or experience detrimental deformation during proof testing. Proof-test fluids shall be compatible with the structural materials used in the COPV and not pose a hazard to test personnel. The proof test fixture shall emulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure driven expansion of the vessel. The temperature shall be consistent with the critical use temperature, or test pressures shall be suitably adjusted to account for worst-case temperature effects on static strength and/or fracture toughness.

5.1.3 Leak Testing

The COPV shall be leak tested at MEOP or greater. The maximum leak rate shall be as specified in the vessel performance or procurement specification.

5.2 Qualification Testing

Qualification tests shall be conducted to demonstrate that all design requirements are met. The qualification test procedure shall be approved by the procurement agency prior to the start of qualification testing.

As a minimum, the following tests shall be conducted on all new or substantially modified COPV designs:

Safe-life demonstration per Section 5.2.1, or LBB demonstration according to Section 5.2.2

(a) Acceptance test per Section 5.1

(b) Pressure cycle testing per Section 5.2.3

(c) Vibration/External load testing according to Section 5.2.4

(d) Leak testing according to Section 5.1.3

(e) Burst testing according to Section 5.2.5

Qualification testing of COPVs that are similar to previously qualified vessels may be reduced subject to the approval of the procurement agency and appropriate range safety authority.

If required, damage tolerance testing shall be conducted according to Section 4.2.10.3. The test article(s) may be the same as the ones used previously or may be separate as defined in the test plan.

When conducting qualification testing, the test fixtures support structures, and methods of environmental application shall not induce erroneous or unrealistic test conditions for the intended application. The types of instrumentation for measuring stresses and displacements and their locations in qualification tests shall be based on the results of the stress analysis (Section 4.2.5). Additional instrumentation shall be installed to provide complete monitoring and control of the test fixtures and hardware including temperature, pressure, and other critical parameters. The instrumentation and test plan shall be formulated to provide sufficient data to ensure proper application of input loads, pressures, environments, and vessel responses to allow assessment against accept/reject criteria, which shall be established prior to test. The sequences, combinations, levels, and duration of loads, pressure, and environments shall demonstrate that design requirements have been met.

5.2.1 Safe-Life Demonstration

5.2.1.1 Safe-Life Demonstration Testing Using Coupons

Testing shall be conducted on uni-axial coupons which duplicate the materials (wrought material, weld joints on heat-affected zones), processes, and thickness of the liner. The coupons shall contain a surface crack and shall meet the requirements for validity of an appropriate method from a published standard of a recognized standards institute. The surface cracks shall not be smaller in size than the flaw sizes established by the appropriate acceptance NDI methods. The flaw shape parameter, a/2c, shall range from 0.1 to 0.5

A spectrum of liner strains in sequence shall be established for all pressure cycles that are to be applied to the vessel after the initial flaws sizes are established by the NDI methods including autofrettage and proof pressures. The coupon shall be cycled though this spectrum in sequence equal to four cycle times or until the total number of cycles equals 50, whichever is greater. All strains of each pressure cycle hysteresis loop shall be tested including the compressive liner strains at zero vessel pressure. Strain gages shall be used to verify test strains. After completion of cyclic strain testing, the crack shall be leak tested to verify that neither leakage nor fracture has occurred during the application of the 50 strain cycles. As a minimum, two data points shall be tested for each material and form. After completion of cyclic testing, the crack faces shall be separated in such a way that will permit measurement of the initial crack sizes to verify conformance to acceptable NDI limit sizes.

5.2.1.2 Safe-Life Demonstration Using COPVs

A COPV which is representative of the flight COPV (liner materials and processing, liner thickness, COPV configuration and reinforcing composite stiffness) shall be used. Surface cracks shall be put in to the liner at pre-determined locations. An inert fluid shall be used to pressurize the COPV according to the spectrum and procedure described in Section 5.2.1.1. If a representative sub-scale COPV is used, the test pressure shall be modified to produce the same liner strains in the sub-scale COPV as are predicted for the flight COPV. At least two different cracks shall be tested.

5.2.1.3 Sustained Load Crack Growth Demonstration of Safe-Life

If data do not exist, the sustained load crack growth behavior of the liner material shall be determined for all fluids that are introduced into the COPV under pressure. Testing using coupons per Section 5.2.1.1 shall be performed. The strain in the coupon during sustained load testing shall be the liner strain at the appropriate pressure for that fluid. The crack under strain shall be exposed to the fluid for a minimum of 1000 hours.

The crack faces shall be separated after testing to verify initial crack sizes. Any evidence of sustained load crack growth in any fluid shall require determination of the threshold strain below which growth in that fluid does not occur. The COPV shall be designed so that the applied strain for a given fluid at its maximum pressure is below the threshold strain for sustained load crack growth in that fluid.

5.2.2 LBB Demonstration Testing

When the strain in the liner is elastic at MEOP, LBB shall be demonstrated by analysis, test, or similarity according to Section 4.2.9. When the strain in the liner exceeds the strain at which linear elastic fracture mechanics is applicable at MEOP then the LBB failure mode shall be demonstrated by test or similarity. LBB verification shall establish that all critical areas exhibit LBB.

5.2.2.1 LBB Demonstration Using Coupons

Testing shall be conducted on uniaxial coupons, which duplicate the materials (wrought materials, weld joints or heat affected zones), processes and the thickness of the COPV liner. The coupons shall start with a surface-crack per Section 4.2.9 and shall meet the requirements for validity of an appropriate method from a published standard of a recognized standards institute for a crack whose length equals ten times the coupon thickness. Cycle loads shall be applied to the test specimen to generate a peak strain corresponding to the strain at MEOP, as determined by analysis. LBB failure mode is demonstrated if the surface crack and breaks through the thickness and grows to a length that is ten times the coupon thickness without causing the coupon to fracture.

5.2.2.2 LBB Demonstration Using a COPV

A COPV, which is representative of the flight COPV (liner material, processing and thickness, configuration, and reinforcing composite stiffness and thickness) shall be used. Surface cracks shall be put into the liner only at locations and orientations that are most critical to LBB response. An inert fluid shall be used to pressurize the COPV. Pressure cycles shall be applied to the COPV, with the upper pressure equal to MEOP. LBB failure mode is demonstrated if the crack leaks the pressure from the COPV at MEOP before catastrophic failure occurs.

5.2.3 Pressure Cycle Testing

Pressure cycling on COPV(s) shall be performed according to Table 1.

The fluids used for pressure cycling shall be compatible with the structural materials used in the COPV and not pose a hazard to test personnel.

The COPV shall be leak tested after pressure cycling to verify compliance with the requirements.

The pressure cycling test fixture shall emulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure driven expansion of the vessel. The requirement for application of external loads in combination with internal pressures during testing shall be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads shall not be required. If the application of external loads is required, the load shall be cycled to limit for four times the predicted number of operating cycles of the most severe design condition (e.g., destabilizing load with constant minimum internal pressure or maximum additive load with a constant maximum expected operating pressure).

The temperature shall be consistent with the critical use temperature, or test pressures shall be suitably adjusted to account for worst-case temperature effects on static strength and/or fracture toughness.

5.2.4 Vibration/External Load Testing

A maximum expected flight-level vibration environment shall be established from the predominant vibration source encountered during the mission. Qualification testing shall be performed using an environment that produces twice the power for three times the duration for each orthogonal axis. Vibration testing shall be conducted at the launch pressure condition with the vessel mass being equivalent to the operational configuration.

5.2.5 Burst Test

Burst testing shall be conducted to verify compliance to the burst factor requirement defined in Section 4.2.2 in compliance with the verification requirements of Table 1.

The design burst should be maintained for a period of time sufficient to assure that the proper pressure is achieved. The vessel shall not burst prior to the end of this period of time. After demonstrating the burst pressure, the pressure shall be increased at a controlled rate until vessel burst occurs.

The burst test fixture shall simulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure driven expansion of the vessel.

Table 1. Qualification Pressure Test Requirements

Test Item	Life Cycle Test, Demonstrate No Detrimental Effects (1)	Burst Test, Demonstrate No Burst at (2)
Vessel #1 (3) Vessel # 2	Cycle for 4 times service life, including proof tests (4)(5)	Burst Factor x MEOP Burst Factor x MEOP

NOTES

(1) Detrimental Effects means causing unacceptable, unusual, unplanned, or out of specification damage and/or rejectable indication, such as deformation, cracking, or leaking.

(2) Unless otherwise specified by the procurement agency and launch site safety office having jurisdiction, after demonstrating no burst at the design burst pressure test level, increase pressure to actual burst of vessel. Record actual burst pressure.

(3) Test vessel may be deleted with the agreement of the procurement agency and launch site safety office.

(4) Only cycles having a peak operating pressure that create a liner tensile stress (exceeds the compressive metal liner pre-stress as imposed by the overwrap, as a result of vessel autofrettage) will be considered in the life cycle test.

(5) If the total number of pressure cycles at MEOP or above times four (4) is less than 50 cycles, the differences required to meet the 50 cycles minimum, must be demonstrated by continuing to cycle from zero pressure to MEOP and back to zero pressure until the 50 cycles minimum is met. “Zero pressure” may be as high as 5% of the test pressure.

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